# Human-System Integration in Autonomous Satellite Tasking

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**Abstract**

We describe the design and initial testing of Draper's Earth Phenomena Observing System (EPOS) a simulation testbed for algorithms being developed for autonomous reconfiguration of Earth observation satellites. Specifically, this paper addresses EPOS human-system integration (HSI) issues and their impact on overall system design. An initial version of EPOS was analyzed to determine current levels of system autonomy across a range of potential users, including Earth scientists, system operators and algorithm developers. Results will be used to help determine the appropriate levels of automation to be employed in future versions of EPOS.

## 1 Introduction

The research and development community is developing a broad range of new capabilities to autonomously plan and control complex systems, e.g., Air Traffic Control, multiple Earth-observing satellite operations. These capabilities raise significant issues about human-system integration (HSI). We discuss some of these issues in the context of Draper's Earth Phenomena Observing System (EPOS), a simulation testbed being developed to host and test algorithms for optimized autonomous reconfiguration of Earth observation satellites. A companion paper [Abramson et. al. 2001] discusses in more detail the planning problem of the current implementation of EPOS. In this paper, we will describe the larger problem EPOS is being developed to solve, and approaches to automation that explicitly consider HSI issues.

## 2 Problem and Approach

The problem can be expressed as seeking to maximize the total value of observations, where value is defined as a combination of scientific value and importance to human life and property. An observation refers to a satellite's sensors collecting data for a desired location (also known as the "target"). The optimization process is constrained by available platform resources, fuel constraints, and also by the characteristics and constraints relating to sensors, communication, and data processing.

Draper's approach to solving this problem takes the form of a system called the Earth Phenomena Observing System (EPOS). This system consists of a simulation of both a SensorWeb [Ticker and Azzolini 2000] of satellites available for tasking and a ground station for command, control and communication. The job of the system is to determine and implement the solution to the problem stated above. A hierarchical decomposition of the problem is employed to make it more tractable. Decomposition is both by level of decision and functional. Decision level decomposition is required because trying to specify all tasking actions for all satellites for the entire mission in a single module is intractable. EPOS includes seven levels, each responsible for a specific class of decisions, ranging from the system level to the sub-satellite level, as shown in Table 1. A functional decomposition is also employed, since in actuality, implementation of each of these levels

| | | |
|---|---|---|
| 1 | **System** | **Select targets; for each target: does the situation require a set of individual viewing platforms (IVP) or dynamic virtual platforms (DVP)? If so, what are the candidate platforms?**<br>**IVP — each satellite has sensors that are needed for observation of the target**<br>**DVP — a set of satellites that contain the sensors needed for simultaneous observation of the target** |
| 2 | **Configuration** | Which satellites need to be refueled? Which satellites need to be launched? |
| 3 | **Platform Assignment** | If DVPs are required, which satellites form the DVPs? If IVPs are required, which IVPs are to be used for observation? |
| 4 | **Observation** | For each satellite, when and for what target should the sensors be used? |
| 5 | **Maneuver** | For each satellite, when and with what $\Delta v$ should the burns be made? |
| 6 | **Sensor** | For each sensor, when and in which direction should it be pointed? |
| 7 | **Communication** | For each satellite, when and what to communicate? |

**Table 1 – Hierarchical decomposition of EPOS into decision levels. Levels focused on in POC have a gray background.**

involves more than just decision making. Each of the seven levels encompasses the functional activities of situation awareness, situation assessment, plan generation, and execution.

We developed a Proof of Concept (POC) version of EPOS in order to get early insight into the benefits of EPOS and to begin examining some of the key technology challenges ahead of us. The POC features a simplification of the full EPOS problem. In the POC the objective is to maximize the total *number* of observations,

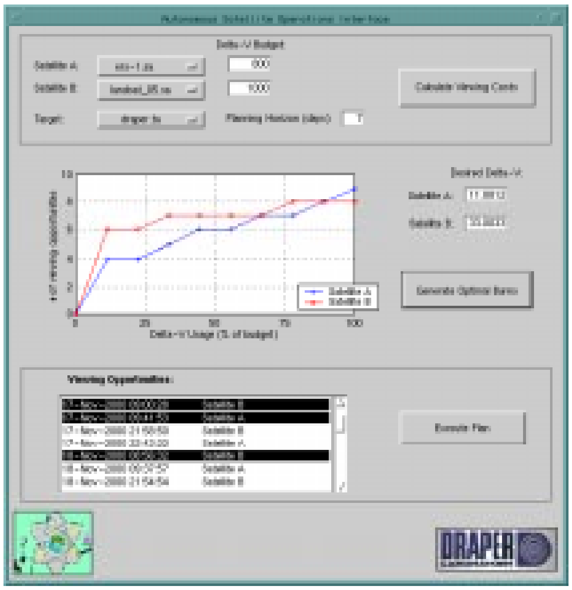

**Figure 1 – Screenshot of the POC graphical user interface**

constrained by available platform resources and fuel constraints. The user selects a single target on Earth and the time horizon over which observation is desired. The user then selects two satellites that will be used in making the observations and specifies a delta-V budget for each satellite. The delta-V budgets could be physical maximums for the satellite, but more generally will be budget allocations made by the user directly or by higher planning levels of the system. The POC system then automatically produces curves for each satellite, trading off the number of successful viewing opportunities that can be achieved versus the amount of budgeted fuel that would need to be expended, as illustrated in Figure 1 in what are called "coverage curves." Maneuver plans and observations plans (defined in Table 1) are automatically generated to achieve the user-selected number of viewing opportunities and then displayed in the POC GUI. The automated calculations described above are performed by the observation planner and maneuver planners, the two levels in Table 1 that have been addressed by the POC. The details of the orbital dynamics and optimization employed for the POC are described in the companion paper.

Future versions of EPOS will build upon this initial capability, as more of the decision levels shown in Table 1 are implemented. For example, later versions of EPOS will have the individual satellite fuel budgets automatically determined by planning levels that examine more global aspects of the situation. Figure 1 shows a screen snapshot of the graphical user interface for the POC.

## 3 Human System Integration

There are several types of humans involved with EPOS: the Earth scientists that initiate requests for phenomena observation, the EPOS operator, and algorithm developers. The EPOS operator is the proxy for the system operator of a real SensorWeb. We are examining how these users interact with the system in order to design a system that can accommodate different levels of automation for different users, while retaining consistency across all planning levels. As a guide to determining *appropriateness*, we examine Sheridan's levels of automation [Parasuraman, Sheridan, and Wickens 2000]. We then analyze the POC system's two decision levels, observation and maneuver, against the Sheridan framework.

### 3.1 Sheridan's Levels of Automation

Sheridan describes 10 levels of automation of decisions ranging from low automation (the computer offers no assistance and so human must make all decisions and take all actions) to fully automated (the computer decides everything, ignoring the human). The full list of Sheridan's levels of automation, coming from [Parasuraman, Sheridan, and Wickens 2000], is shown in Table 2.

| | | |
|---|---|---|
| HIGH | 10 | The computer decides everything, acts autonomously, ignoring the human. |
| | 9 | informs the human only if it, the computer, decides to, |
| | 8 | informs the human only if asked, or |
| | 7 | executes automatically, then necessarily informs the human, and |
| | 6 | allows the human a restricted time to veto before automatic execution, or |
| | 5 | executes that suggestion if the human approves, or |
| | 4 | suggests one alternative |
| | 3 | narrows the selection down to a few, or |
| | 2 | The computer offers a complete set of decision / action alternatives, or |
| LOW | 1 | The computer offers no assistance: human must take all decisions and actions |

**Table 2 – Sheridan's Levels of Automation of Decision and Action Selection**

There are four classes of functions that can be automated according to Sheridan, which map to those described in the functional decomposition of EPOS described in Section 2 – situation awareness, situation assessment, plan generation, and execution. Each of these functions can be executed at a different level of automation. In addition, the decomposition of EPOS includes seven decision levels, each of which contains the four functions. Thus, referring to the automation in a complex system like EPOS involves the automation levels of many functions (i.e., up to 28 in a full EPOS).

## 3.2 Analysis of Proof of Concept

A key HSI goal is that of understanding the automation issues regarding EPOS, so that over time the system will achieve high utility to any class of user by automating functions in every decision level appropriately. This goal is initially addressed by examining the automation existing in the POC version of EPOS. The POC contains two levels of decision making: maneuver planning and observation planning. For each of these decision levels we describe the current level of automation, and what range of automation is anticipated in future versions of EPOS and how it would affect EPOS users. Additionally, a short discussion of the overall POC system automation is discussed.

An important distinction should be made between EPOS and the type of systems that are analyzed in Sheridan's framework. EPOS will provide a capability that doesn't currently exist, and would be unlikely to be implemented in a fully manual mode – i.e., there is a required minimum level of autonomy to perform its functionality. The systems primarily focused on by Sheridan are ones in which automation is being used to replace roles currently being performed by humans. Many of these systems (e.g., Air Traffic Control) are safety critical, and an automation failure may lead to loss of lives. This drives some of his evaluation metrics towards human performance and automation reliability. New metrics may be required for assessing EPOS performance, where automation failure may result in the non-safety critical outcome of key observations being missed. In fact many of the observations chosen by scientists may be driven by a desire to save lives. The observation of such life threatening phenomena as earthquakes, volcanoes, tsunami, and search and rescue are all within the scope of EPOS. But the failure of EPOS in achieving adequate observation would not be directly responsible for any resulting loss of life.

Sheridan's work focuses on the effect of automation on the human whose work is now being done automatically. In EPOS, at least three different types of users are involved in human system integration: Earth scientists using EPOS to plan observations of specific targets and hence providing science requirements, EPOS system operators using EPOS to meet these science requirements given the available SensorWeb resources, and algorithm developers who provide the underlying capability for EPOS automation. Our analysis below addresses how this automation would impact these three types of users.

**Maneuver Planning.** In the POC, maneuver planning is a simplified pre-mission activity that includes perfect situation awareness of orbital parameters as inputs and calculates the resulting burns needed to achieve a target set of orbital parameters. It therefore only makes sense to talk about one functional component of this decision level, the plan generation function which determines the time and delta-V for each burn. The maneuver planner operates at autonomy level 10 (fully autonomous).

For future versions of EPOS, higher fidelity astrodynamic models than the two-body assumptions employed for POC will be utilized in order to increase accuracy of the maneuver plans. In order to accomplish this, while still maintaining other important system characteristics, like real-time performance, a higher decision level planner might be responsible for selecting the astrodynamic model to be utilized by the maneuver planner. A goal would be to automate the selection of astrodynamic model, if possible. Scientists would prefer this decision be automated to avoid unnecessary interactions on their part. The system operator would want the ability to manually adjust the astrodynamic model being used as he or she is primarily concerned with maintaining real-time performance of the overall system, and higher fidelity astrodynamic models might reduce the responsiveness of the system to an unacceptable level. Algorithm developers will want to be able to operate the system at any levels appropriate for scientists and system operations, as well as at other levels for algorithm development and testing.

**Observation Planning.** In the POC, observation planning is a pre-mission activity that also utilizes perfect situation awareness as input. This decision level features two automated components: situation assessment and decision making. The situation assessment component provides the user with the observation / fuel tradeoff curves illustrated in Figure 1, from which the user selects the desired operating point. This automation is at level 2 (computer offers a complete set of decision action alternatives) of Sheridan's automation scale. The decision making function is a autonomy level 10 (fully autonomous) capability, utilizing an integer programming based solution for optimizing which viewing opportunities will be successfully achieved in meeting the user-selected point in the observation / fuel tradeoff curves.

For future versions of EPOS, the goal will be to maintain fully autonomous optimization of observations for all users, but operating with higher fidelity models, including more complex sensor models than that employed for POC. Scientists will want to maintain this at level 10 autonomy to avoid unnecessary system interactions. The system operator, on the other hand, is primarily concerned with maintaining real-time performance of the overall system.

Faced with the introduction of higher fidelity models, which might run more slowly, the system operator would prefer running at below full automation levels using "quick and dirty" solutions that require human intervention, if this human intervention allowed overall system processing to maintain real-time performance. Algorithm developers again will want to be able to operate the system at any levels appropriate for scientists and system operations, as well as at other levels for algorithm development and testing.

The selection of the operating point on the observation / fuel tradeoff curve can be automated up to a minimum of autonomy level 4 (suggests one alternative) and to autonomy level 10 (fully autonomous) as this planner interacts with higher decision level planners (e.g., the platform assignment planner).

**POC System Decision Level Automation.** As discussed above, several components of the POC system are automated at differing levels of automation, including full automation. It is interesting to note however, the top decision level of the POC system is at a low level of automation. In the current system, the user must provide many pieces of information, such as satellite fuel budgets, planning horizons and actual satellites, without any aid from the system.

## 4 Future Automation within EPOS

For future versions of EPOS, the goal will be to increase the level of automation in each decision level appropriately, as determined from the results of the POC and future problem formulation and solution issues. EPOS will be developed so that both scientists and system operators would have the capability to interact with the system at varying levels of automation. One major technical challenge in the development is maintaining consistency of plans across the various decision levels at whatever level of automation a user is interacting with the system. An example of a difficult case is when three (or more) decision levels are highly autonomous and the user wishes to make decisions manually at the middle level of the three. In that case the decision levels above and below the manual level must still work consistently with the middle level.

## 5 Acknowledgments

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